SWINDEN QUARRY: A CASE STUDY OF DETECTING, SURVEYING AND MANAGING CAVES WITHIN QUARRIES

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ABSTRACT

Caves within quarries are difficult to detect and their presence can cause serious problems for quarry operators. When caves have historically been found, it has been difficult to fully determine their extent and nature in order to devise a practical and safe solution for managing them.

Using a recent case study; Swinden Quarry in North Yorkshire, this paper describes the techniques employed to manage caves at the site, and how new subsurface 3D surveying technology can be used to accurately map their extent and enabling a targeted solution to be designed, to make them safe.

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INTRODUCTION

Swinden Quarry is located immediately north of the village of Cracoe, *c.*3.5km south west of Grassington and *c.*10km north of Skipton, within the Yorkshire Dales National Park in North Yorkshire, as shown on Figure 1. The deposit at Swinden Quarry is a Carboniferous reef limestone complex with unpredictable karst topography. To date, most cavities encountered have been either small or naturally filled with debris and so have not presented a safety issue. However, in 2011 a seemingly innocuous cavity was encountered that, when probed appeared to be in the region of 28m deep. With machinery in excess of 200 tonnes traversing the quarry floor, gaining an accurate understanding of the cave's geometry was essential in order to mitigate the risk it posed. This paper is a case study of how caves are managed at Swinden quarry, highlighting associated problems and how, in one particular instance, a large cave was dealt with from detection, through investigation to its ultimate remediation to make the cave safe.

GEOLOGICAL SETTING

Swinden Quarry extracts Lower Carboniferous (Mississippian) aged limestones that were deposited between the shallow ocean shelf environments of the Askrigg Block to the north and the deeper marine environments of the Craven Basin to the South, as shown in Figure 2. The margin between the two was actively being deformed both during and after the deposition of the limestone, resulting in the bedrock being folded and faulted. Along this margin, a series of reefs, known as the Craven Reef Belt (Mundy, 2000) were formed. Swinden Quarry, part of the Craven Reef Belt sits within Cracoe Hill which gives its name to the cluster of Cracoean Reefs formed in the area between Grassington and Cracoe, which includes Skelterton, Stebden and Elbolton. These reefs are shown on Figure 2 and on Figure 1 as distinct hill features. These hills appear to be associated with underlying anticlinal structures and their current surface expression broadly represents the shape of the original reef geometry.

Locally, the stratigraphy of Swinden Quarry can be summarised as Carboniferous aged rocks starting with a foundation of pre-reef bedded limestone (Skelterton and/or Threapland limestone) upon which a reef like complex has evolved, comprising both massive and bedded limestone (Mundy, 2000). Flanking this reef complex are a series of limestone debris beds or breccias comprising reworked limestone and black shale. The Bowland Shale overlies the limestone to the north, west and east. Recent superficial deposits, including boulder clay and alluvium, infill valley features incised in to the Bowland Shale along the north west and south eastern flanks of Cracoe Hill. As can be seen on the schematic cross sections on Figure 3, it can be considered somewhat isolated from other limestone outcrops in the area.

The caves within the limestone are dissolution features, cross cutting all strata thus far encountered within the quarry. Typically they are infilled with clay and the age of their formation is unknown. The main problem posed by the presence of the caves relates to the production process. The soft infill within the caves means

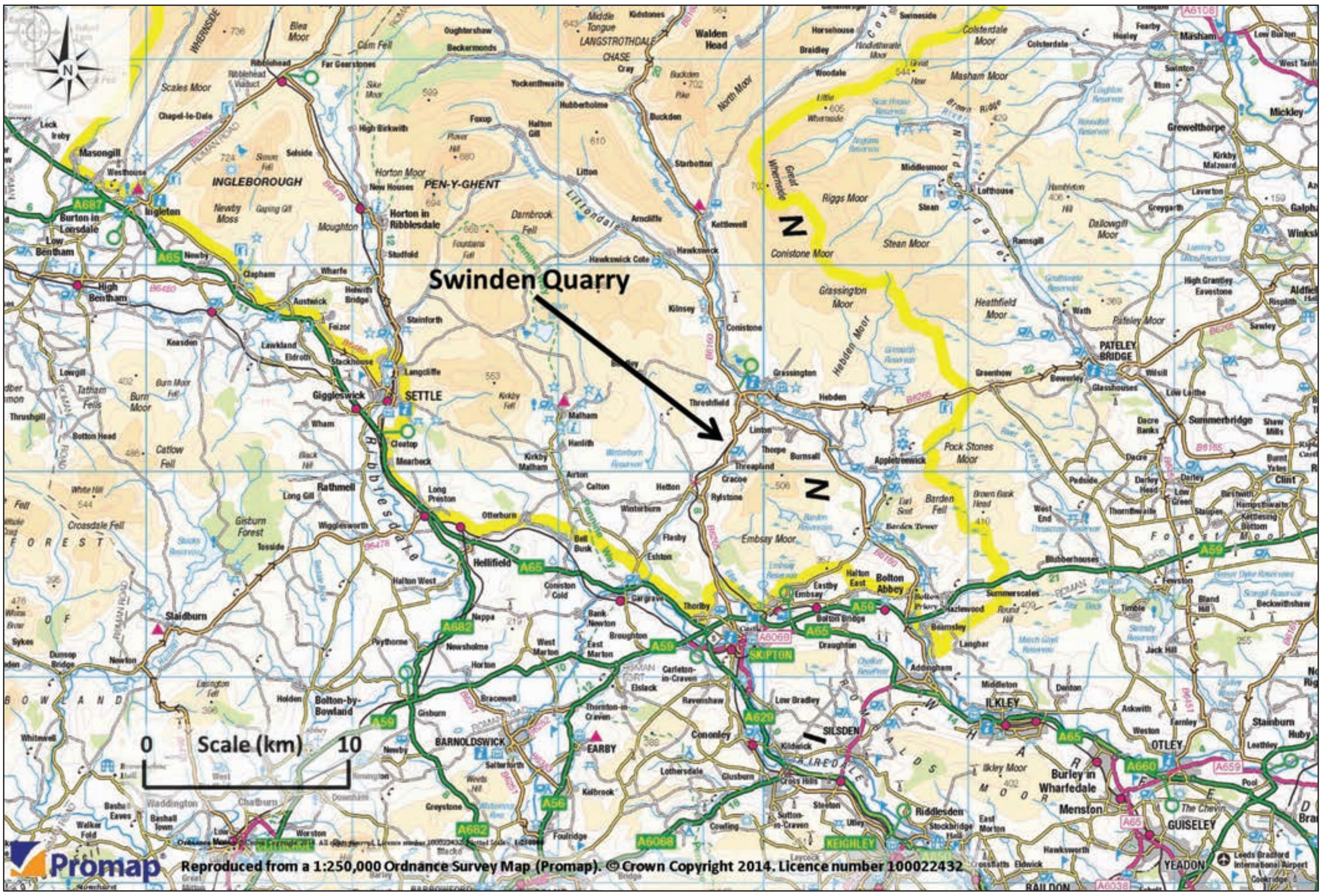

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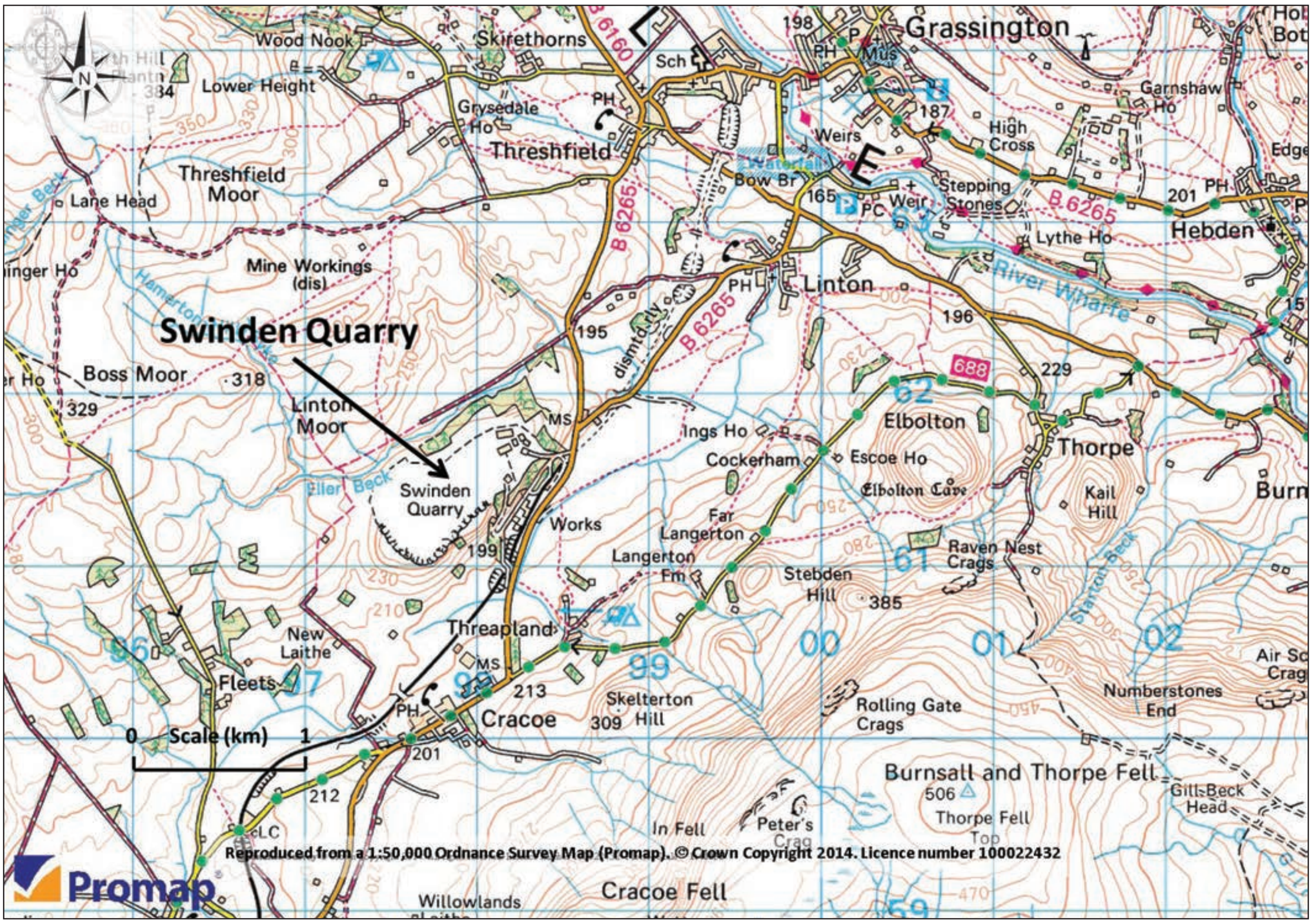
Figure 1. *Location of Swinden Quarry. The top image shows its regional position and the bottom image the local situation with the quarry, the village of Cracoe and the reef knolls of Elbolton, Stebden and Skelton visible (as on Figure 2).*



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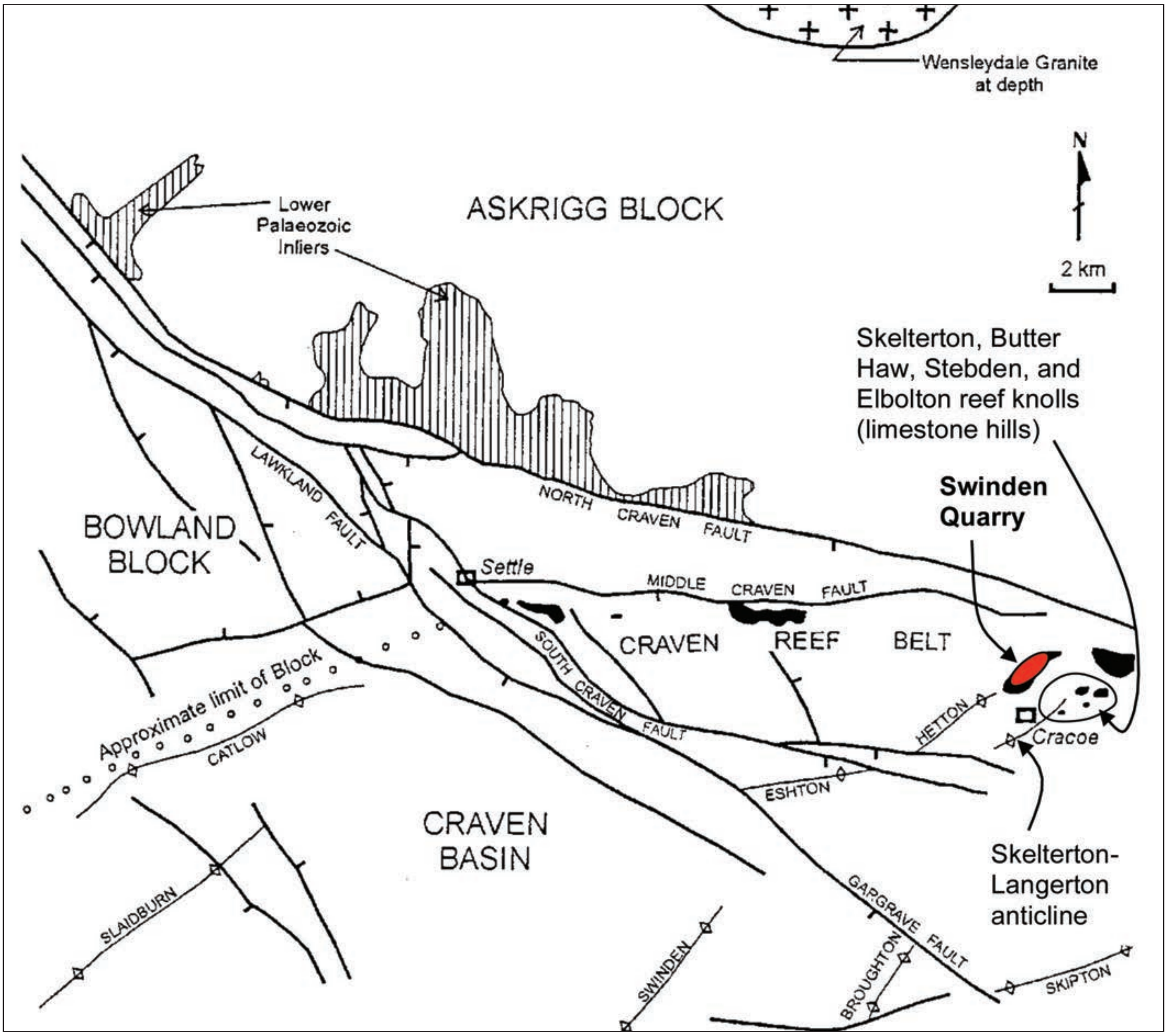


Figure 2. *Regional structural geology (modified from Arthurton et al., 1988). The settlements of Settle and Cracoe are shown. Solid black areas denote reef structures within the Craven Reef Belt.*

that drill holes fail to remain open and thus prevents charging with explosives. Once blasted, the presence of the clay in the blast pile does not pose quality issues as the clayey material is removed via a scalping (screening) process within the fixed processing plant. Prior to encountering the large open cave in 2011, no large open cave had been encountered within the quarry.

MANAGING CAVES AT SWINDEN QUARRY

In quarrying, unlike in civil engineering where static features are built, quarries are dynamic working environments where, using mobile equipment the thickness of the supporting roof beam is progressively removed from above the cave.

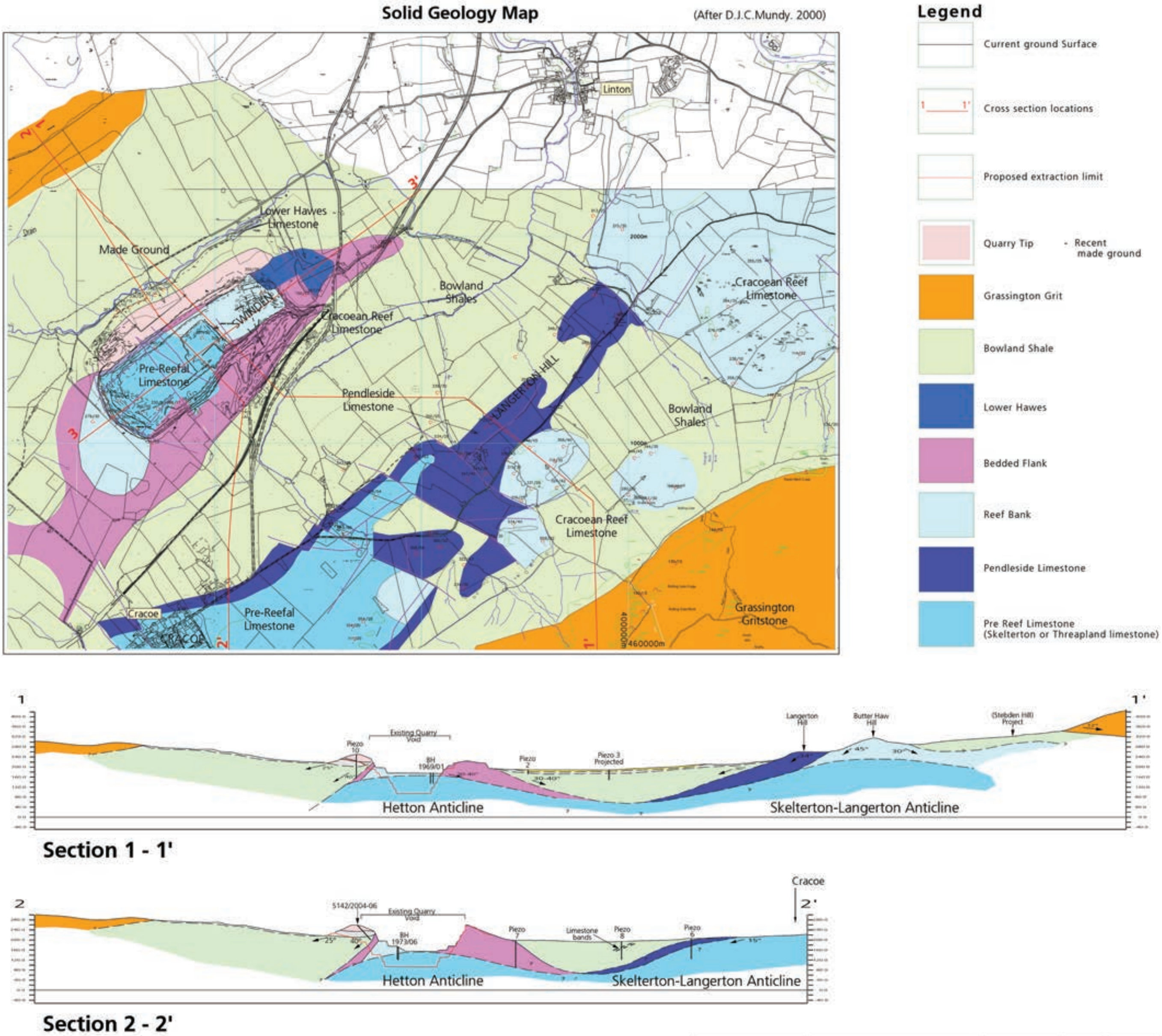
The finding of caves at Swinden is relatively common and the process by which these caves are managed is shown in Figure 4.

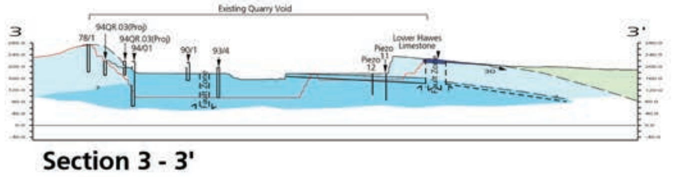
Any system for detecting caves has to be proportionate to the risk and be practicable, therefore it is important to characterise the nature of the problem in the first instance. Karstic caves are unpredictable and notoriously difficult to detect through proactive investigation alone; therefore any approach needs to be a mix of proactive investigation and ongoing observation. Once a potential cave is detected, further reactive investigation will be required to determine the risk it represents and to inform how the cave will be managed and remediated.

Characterisation

To understand the characteristics of voids that may be present at a particular site, several points need to be considered. Appraising the regional and local geology will identify strata prone to natural dissolution, whilst also highlighting the potential for problematical man-made voids primarily resulting from mining activities.

In the case of Swinden, man-made voids have been ranked unlikely. Cracoe Hill, whilst on the edge of one of the most historic productive lead mining regions in the UK, seemingly was not itself part of the ore field, with





Askrigg Block	Craven Basin	Stages	Series	Age
Grassington Grit		Pendleian	Namurian	UPPER CARBONIFEROUS (Pennsylvanian)
	Upper Bowland Shales			
Wensleydale Group (including Upper and **Lower Hawes Limestone**)	**Lower Bowland Shales**	Brigantian	Visean	LOWER CARBONIFEROUS (Mississippian)
Malham Formation **(including 'Cracoan' Reefs)** **Bedded Flank** **Reef Bank**	**Pendleside Limestone**	Asbian		
Kilnsey Limestone (**Skelterton Limestone**)	Worston Shales	Holkerian		
Kilnsey Limestone with Mudstone (**Threapland Limestone**)		Arundian		
Chapel House Limestone				
Non Sequence	Thornton Limestone Thornton Shales with Limestone	Chadian		
Stockdale Farm Formation	Chatburn Limestone	Ivorian	Tournaisian	
Basement				ORDOVICIAN & SILURIAN

Figure 3. *Geological cross sections, stratigraphy and solid geology map of the quarry.*

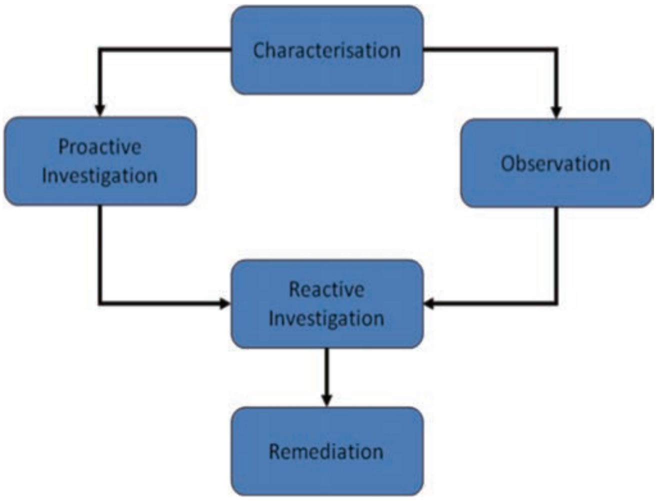


Figure 4. *Flow diagram for cave management at Swinden Quarry.*

only minor mineralisation being noted within the quarry and mining records showing no significant operations. Field mapping only identified what appear to be small occurrences of mining spoil from what may have been explorative excavations across Cracoe hill. The structural setting of the Cracoe reef, south of the North Craven Fault, appears to have kept the deposit isolated from the processes that created the nearby ore field.

Swinden sits within a karstic landscape. Waltham and Fookes (2005) believe the likely presence and nature of karstic features on a given site can be judged by appraising the regional setting using a classification system summarised in their 2005 paper. Being on the edge of the Yorkshire Dales, home of some of the UK's largest cave systems and well known karstic landscapes, Swinden has to be regarded as being potentially prone to these features on a macro scale. But as with any macro understanding, it may not translate accurately to the local setting as demonstrated by the ore field analogy, and a local understanding is key.

Mapping and site records identify two principal types of karstic features within the quarry, these being karren runnels; clay infilled sub-vertical wedge shaped joints, reaching a maximum width of 2-3m at surface and tapering downwards, the deepest of which can reach up to 5-10m depth. The other type, and most problematic for quarrying operations are the presence of underground cavities. In order to understand the risk they represent, the nature of the cavities and the geotechnical properties of the host rock at Swinden have been characterised using the method outlined by Waltham and Fookes (2005). Table 1 sets out the key aspects that require consideration under this system against the observations from Swinden. The considerations can be split in to two main areas; the first area relates to the nature of the anticipated caves, including dimensions, shape and nature of the infill (if present), but also how they could potentially relate to each other. The second area considers the nature of the host rock including its overall likely performance based upon a rock mass rating. The rock mass rating takes into account the intact rock strength of the solid rock, but also the presence and nature of other weakening factors such as fracturing, weathering and mining related blast damage. This is important because the strength of the overall rock mass will be less than the strength of a single intact piece of rock.

In the case of Swinden the rock has been assessed using Laubschers Mining Rock Mass Rating (MRMR(2)) (1990). Mohr (2008) states that the limestone rock mass contains widely to very widely, very irregular shaped, rough stepped jointing. Often the joints are open and vuggy due to karstic weathering. The limestone is very competent and extremely strong, showing an average intact rock strength of between 80 and 130MPa. The Laubscher MRMR rock mass classification indicates the limestone to be a good to very good quality rock mass.

Waltham and Fookes (2005) refer to an informal guideline known as the 70% rule which states that stability can be expected if the thickness of the roof beam above the cave is at least the equivalent of 70% of the width of the cave. This makes the assumption as outlined in Table 1, that the rock is strong (with an unconfined compressive strength of at least 80MPa) with good rock mass characteristics. This is considered to be a conservative approach based upon destructive testing carried out upon model caves of 4m width using limestone with a UCS of 80MPa. These tests assumed a Safe Bearing Pressure (SBP) of 2MPa with the 70% being determined as the point where the relationship between roof thickness for a jointed limestone equalled a failure load 3 times that of the SBP i.e. 6MPa, thereby building in a Factor of Safety of 3.

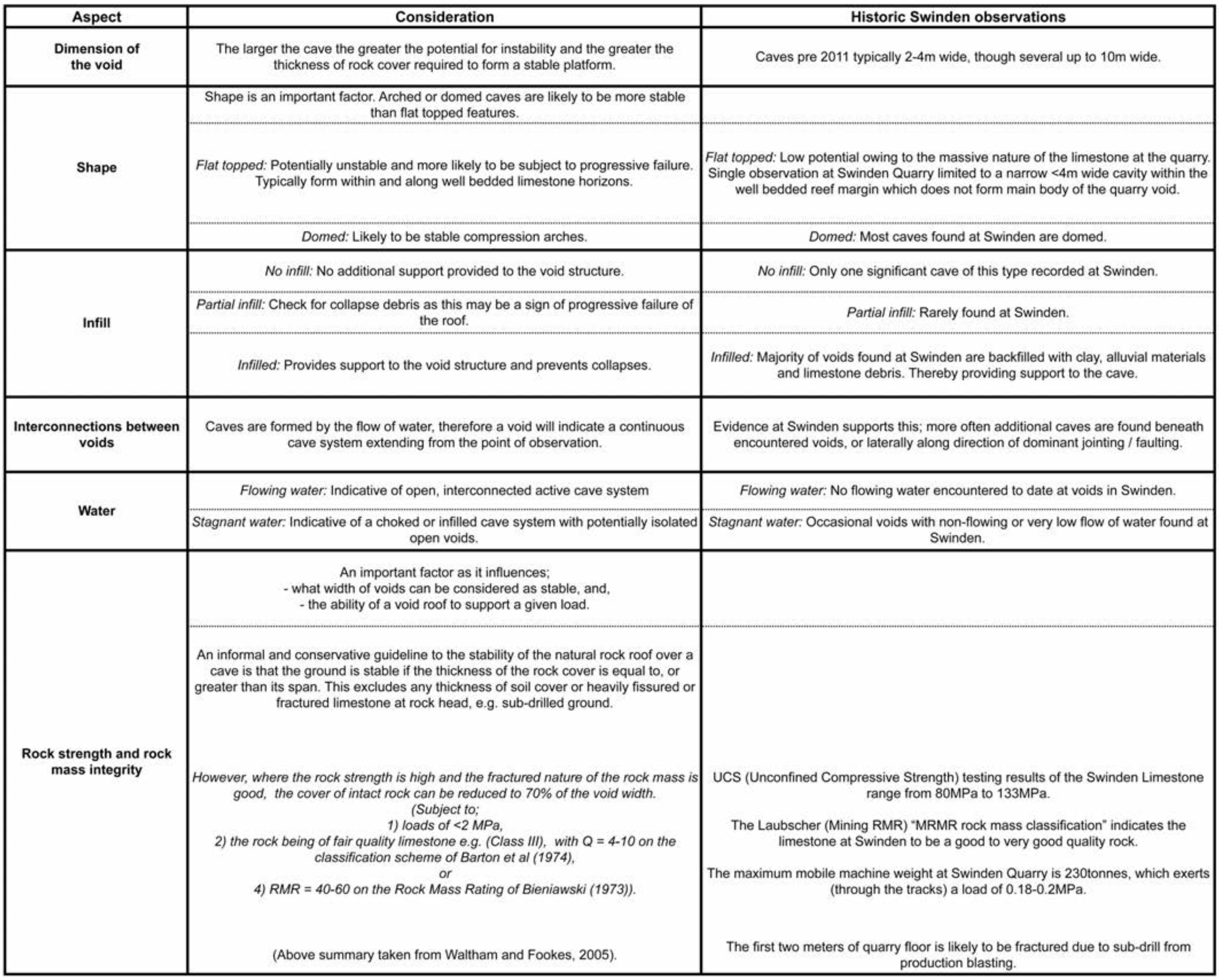
At Swinden Quarry the greatest risk from cave collapse is within the dynamic part of the quarry; the area of extraction where two large machines are employed, a CAT 5130 excavator and a Nordberg LT160 mobile crusher, both of which routinely traverse the quarry floor and each represent a load of 0.2MPa, considerably less than the SBP expected of a sound limestone as stipulated by Waltham and Fookes (2005).

It is therefore concluded that the whilst Waltham and Fookes (2005) utilise two alternative rock mass classification systems, (Barton et al (1974) Q system and Bieniawski (1973) Rock Mass Rating), the rock mass at Swinden Quarry as classified using the MRMR system, is sufficiently comparable to warrant the utilisation of the 70% rule in appraising and managing the risk of caves at Swinden Quarry, particularly given the nature of the potential loading.

Using the 70% rule allows the target depth for the investigation of caves to be determined. In a quarry, the investigative depth has to take in to account the depth of stone being removed by the advancing face, plus the minimum acceptable thickness of cover above the cave (beneath the new quarry floor level). At Swinden, the working face height is 20m, so as an example, a 15m wide cave would require an investigation to a depth of 32.5m as shown in Table 2.

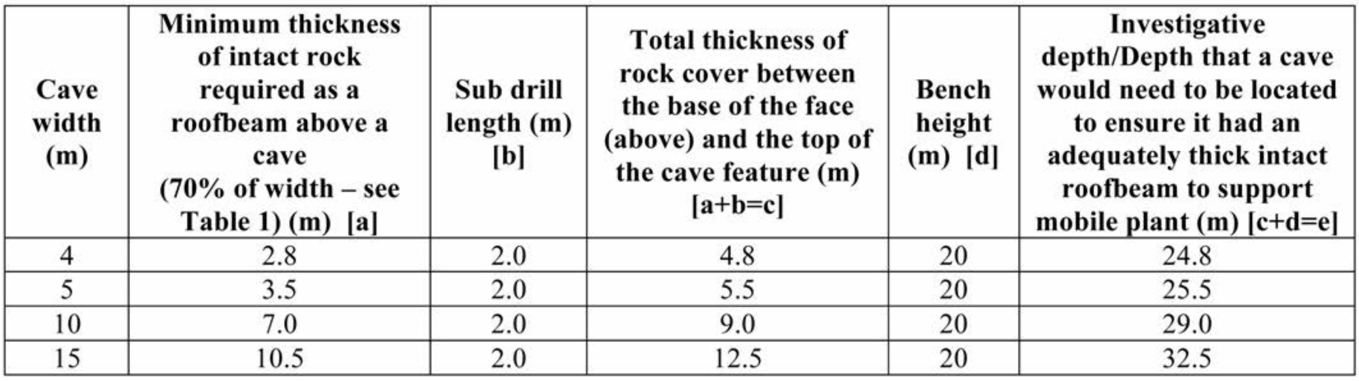
Proactive investigation

The methods used for detecting caves can be split into intrusive and non-intrusive techniques. Prospecting for caves can be costly and time consuming and no one method is suitable across all sites. It is important when planning any survey programme to take into account the limitations of the techniques available, the site characteristics, and the cost.



Aspect	Consideration	Historic Swinden observations
Dimension of the void	The larger the cave the greater the potential for instability and the greater the thickness of rock cover required to form a stable platform.	Caves pre 2011 typically 2-4m wide, though several up to 10m wide.
Shape	Shape is an important factor. Arched or domed caves are likely to be more stable than flat topped features.	
	Flat topped: Potentially unstable and more likely to be subject to progressive failure. Typically form within and along well bedded limestone horizons.	*Flat topped:* Low potential owing to the massive nature of the limestone at the quarry. Single observation at Swinden Quarry limited to a narrow <4m wide cavity within the well bedded reef margin which does not form main body of the quarry void.
	Domed: Likely to be stable compression arches.	*Domed:* Most caves found at Swinden are domed.
Infill	*No infill:* No additional support provided to the void structure.	*No infill:* Only one significant cave of this type recorded at Swinden.
	Partial infill: Check for collapse debris as this may be a sign of progressive failure of the roof.	*Partial infill:* Rarely found at Swinden.
	Infilled: Provides support to the void structure and prevents collapses.	*Infilled:* Majority of voids found at Swinden are backfilled with clay, alluvial materials and limestone debris. Thereby providing support to the cave.
Interconnections between voids	Caves are formed by the flow of water, therefore a void will indicate a continuous cave system extending from the point of observation.	Evidence at Swinden supports this; more often additional caves are found beneath encountered voids, or laterally along direction of dominant jointing / faulting.
Water	*Flowing water:* Indicative of open, interconnected active cave system	*Flowing water:* No flowing water encountered to date at voids in Swinden.
	Stagnant water: Indicative of a choked or infilled cave system with potentially isolated open voids.	*Stagnant water:* Occasional voids with non-flowing or very low flow of water found at Swinden.
Rock strength and rock mass integrity	An important factor as it influences; - what width of voids can be considered as stable, and, - the ability of a void roof to support a given load.	
	An informal and conservative guideline to the stability of the natural rock roof over a cave is that the ground is stable if the thickness of the rock cover is equal to, or greater than its span. This excludes any thickness of soil cover or heavily fissured or fractured limestone at rock head, e.g. sub-drilled ground. *However, where the rock strength is high and the fractured nature of the rock mass is good, the cover of intact rock can be reduced to 70% of the void width. (Subject to; 1) loads of <2 MPa, 2) the rock being of fair quality limestone e.g. (Class III), with Q = 4-10 on the classification scheme of Barton et al (1974), or 4) RMR = 40-60 on the Rock Mass Rating of Bieniawski (1973)).* (Above summary taken from Waltham and Fookes, 2005).	UCS (Unconfined Compressive Strength) testing results of the Swinden Limestone range from 80MPa to 133MPa. The Laubscher (Mining RMR) "MRMR rock mass classification" indicates the limestone at Swinden to be a good to very good quality rock. The maximum mobile machine weight at Swinden Quarry is 230tonnes, which exerts (through the tracks) a load of 0.18-0.2MPa. The first two meters of quarry floor is likely to be fractured due to sub-drill from production blasting.

Table 1. *Key aspects that are taken into consideration when characterising caves at Swinden Quarry in order to determine the geohazard they represent. The table utilises classification guidance from Waltham & Fookes (2005).*



Cave width (m)	Minimum thickness of intact rock required as a roofbeam above a cave (70% of width – see Table 1) (m) [a]	Sub drill length (m) [b]	Total thickness of rock cover between the base of the face (above) and the top of the cave feature (m) [a+b=c]	Bench height (m) [d]	Investigative depth/Depth that a cave would need to be located to ensure it had an adequately thick intact roofbeam to support mobile plant (m) [c+d=e]
4	2.8	2.0	4.8	20	24.8
5	3.5	2.0	5.5	20	25.5
10	7.0	2.0	9.0	20	29.0
15	10.5	2.0	12.5	20	32.5

Table 2. *Table showing the thickness of rock cover required (as a roofbeam and for investigation purposes) to ensure safe passage of machinery over an open cave at Swinden Quarry.*

Intrusive investigation primarily comprises probe drilling. Fookes and Waltham (2005) quote that "a density of 2500 (boreholes) per hectare is needed to have a 90% chance of finding one cavity 2.5m in diameter". Of note is that the density of holes could be reduced through the use of down the hole geophysics.

Non-intrusive techniques encompass, but are not limited to, ground probing radar, microgravity, electromagnetic resistivity, electromagnetic conductivity and seismic surveys. In their own right, they will not necessarily determine the extent or characteristics of the cave, instead these techniques should largely be treated as a tool to identify anomalies within the substrate that then would require further investigation, most likely in the form of intrusive drilling.

Each of the techniques outlined above have particular constraints and so careful consideration needs to be given before their deployment. At Swinden Quarry, following a desk top study, the majority of the non-intrusive techniques were scoped out as not being suitable. The primary reason for this was the limited, poor resolution offered at the required depths, with many failing to penetrate below 20-30m. Resolution is further diminished in each case, to a greater or lesser degree by:

- The presence of groundwater, which is an issue at Swinden with groundwater present within 5-10m below the quarry floor level.
- Undulating topography and a small quarry floor area (<200-300m diameter), with numerous faces.
- The presence of metal in the form of conveyors and other semi-permanent plant.
- Vibration from continuous operations in the associated mineral processing plant.

As such, a proactive approach to investigating the presence of caves over the active quarry floor at Swinden was judged as impracticable. However, this does not mean that these techniques could not be deployed in the future. Technology is developing rapidly and certain techniques may, and indeed have been beneficial as part of a reactive approach arising from field observations focussing on specific areas of the quarry, as discussed in the next chapter.

Observation and reactive investigation

Due to the erratic nature of karstic landscape features, it is recommended that an observational approach to detecting caves should always be undertaken, regardless of whether a proactive investigation has been carried out.

At Swinden Quarry, the observational approach is the primary approach for reasons described previously. This is based upon the assumption that the main problems arise from cavities and that these are formed by interlinking features that facilitated the flow of water during their formation, regardless of whether the caves are now choked. In other words, where one cavity is found more are sure to follow.

In practice this means that existing caves are mapped as the faces progress, and that new features are recorded and then investigated. This process is shown in Figure 5.

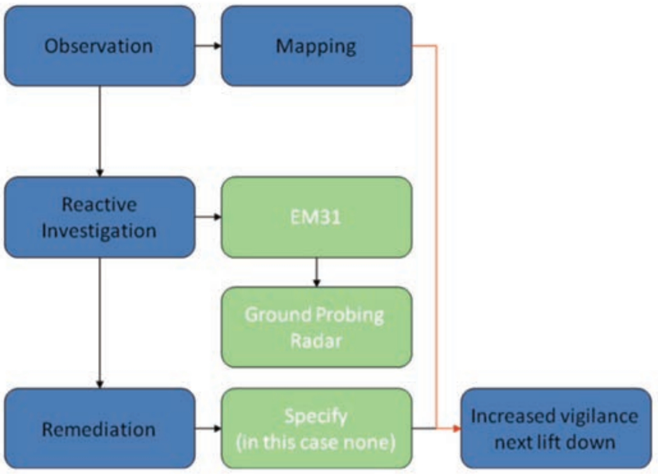


Figure 5. *Process map for observational mapping and reactive investigation of cavities at Swinden Quarry (blue boxes). The green boxes show the investigative techniques used.*

Case study on the investigation, characterisation and remediation of a significant cave at Swinden Quarry

In 2010 one such feature was noted on the 155mAOD (Above Ordnance Datum) level at Swinden Quarry. This appeared to be an innocuous feature, as shown on Figure 6. Initial investigation using a dipmeter indicated it in part to be open. As a result further investigative work was undertaken by the University of Leeds using a combination of EM31 electromagnetic and Ground Penetrating Radar (GPR) surveys. A cave *c*.4m wide at between 1-4mBGL (Below Ground Level) was detected, with the interpretation that the hole was probably infilled with conductive material e.g. clay, as shown in Figure 7. This work also confirmed that the effective depth of these surveys was limited to 4-6mBGL.

The quarry floor was then probe drilled using a conventional blast rig to firstly confirm that the cavity was indeed infilled and secondly to ensure there were no larger cavities at depth. The results of this drilling concurred with the results of the geophysical investigation and further proved that the cavity was clay filled. As a precaution, the area was then demarcated and recorded on the topographic survey so that on the successive bench (the 135m level), the location of this cavity could be found and the area be subjected to greater vigilance.

Across the wider quarry floor, the EM31 and GPR surveys were of limited success due to the fact that both survey methods only provided a shallow depth of penetration, exacerbated by the presence of metal in the form of conveyor structures, groundwater and the topography of the site which comprises relatively small expanses of narrow open quarry floor no more than 70-100m away from a 20m quarry face. These elements all combine to distort the readings from the instruments during surveys.

In 2011 when the quarry worked through the location of the 155m level cave, another cavity was noted at the lower 135m level, as shown on Figure 8. The hole represented the largest open cave encountered to date at the site, being in the region of 2.5m diameter at the surface. When dipped, the cave depth was indicated to be about 28m, though this later transpired to be an over estimate.

Figure 6. *Small cavity on the 155m level, approximately above the location of the large open cave.*

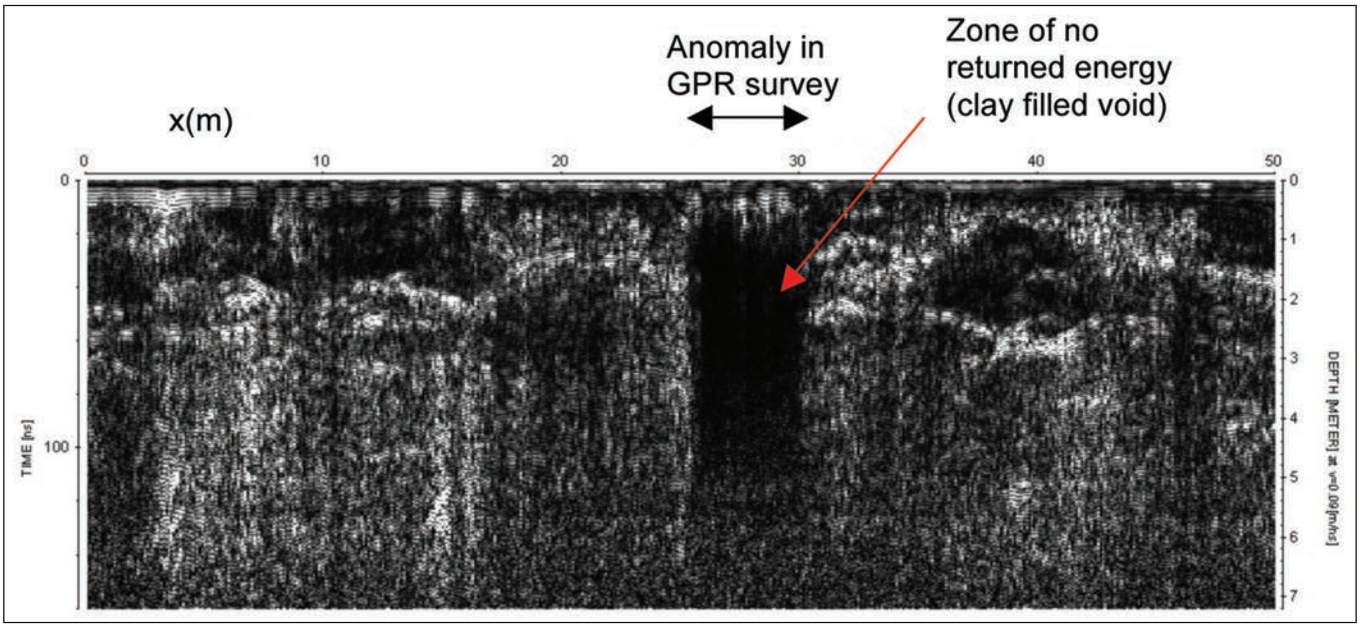


Figure 7. *GPR scan to a depth of 7m, conducted following observation of the open hole in quarry floor on the 155 mAOD level.*

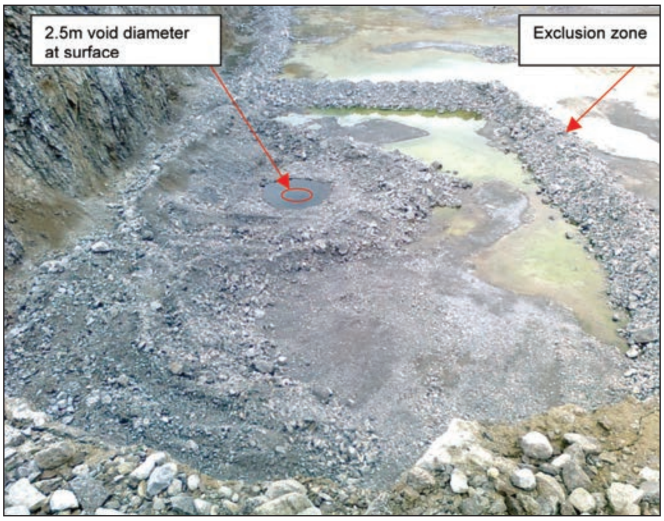


Figure 8. *Photograph showing the cave feature as expressed on the 135mAOD level.*

Investigation options

Several options for investigating the cavity were considered, including cave divers entering the cave and probe drilling. However, instead it was decided to opt for a new, less invasive technique which Lafarge Tarmac considered safer. This would comprise a down the hole scan of the cave, allowing details of the size, orientation and geometry of the feature to be determined.

Subsurface Scanning Limited was engaged to provide the service. Because the hole was flooded, this precluded the use of a down the hole laser profiling system and instead a Imaginex 881a sonar unit was deployed.

Investigation stage 1: Sonar survey

The Imaginex 881a profiling sonar operates at frequencies between 600kHz and 1MHz, which allows the probe to scan up to a range of 100m radius at a resolution of 2-10mm. Normally this type of sensor is used in a horizontal mode, towed behind a boat, but it has been possible to specifically configure this unit to work vertically. This now allows it to access voids at depth by being lowered down vertical boreholes with an internal diameter of greater than 80mm.

The sonar instrument has a built in Heading Pitch and Roll (HPR) sensor to provide orientation for the captured sonar ranges. In order to make use of this facility it was first necessary to ensure that the cavity and drop position were geo-referenced, this was achieved using a differential GPS and total station, allowing the resulting three dimensional model to be shown in context to the quarry cave.

Due to the width of the cave entrance, a large, purpose made tripod (Figure 9) was required to ensure that the cave opening could be spanned and to facilitate the lowering of the sonar unit into the centre of the cave.

Once the tripod was positioned the sonar was lowered to a depth of 14m below the water level where it came to rest, somewhat short of the reported 28m depth from the initial dip by quarry staff. The initial reading showed the unit had come to rest, tilted, at an angle of 43°. The

Figure 9. *Tripod set-up over the cave opening, with the sonar instrument being lowered via the yellow cable.*

unit was then raised until a clearly vertical attitude was achieved and then the sonar gain was adjusted to give a clear image of the cavity wall. Profiles were then recorded at 0.5m intervals as the unit was winched upwards, allowing for a comprehensive picture of the internal shape of the cavity to be built up.

Upon completion of the survey, data processing using the Rhino 3D software was undertaken. The point cloud data generated at the extent of the cavern was extrapolated for each of the 0.5m intervals to build a three dimensional model. The model of each of the incremental 0.5m horizontal slices were geo-referenced using the sonar data and then stacked one on top of the other. The resultant 3D CAD model was then used to produce accurate plans and cross sections and to calculate the volume of the cavity. An array of Computer Generated Imagery (CGI) and Computer Generated Metafiles (CGM) graphics were also used to create interactive 3D models and these were translated into 3D Adobe PDF format to ensure ease of viewing and manipulation.

The cavity was profiled to a depth of 14m below the quarry floor, showing that it comprised an almost vertical 4.5m long pipe to the top, with a diameter of 1.5-2m, opening out into an irregularly shaped cavern below, which at its widest span was just less than 18m. A more detailed understanding of the geometry of the cavern is shown in Figure 10, whilst Figure 11 puts the size of the cave feature into context. The volume of the cavity was measured as approximately 800m^3.

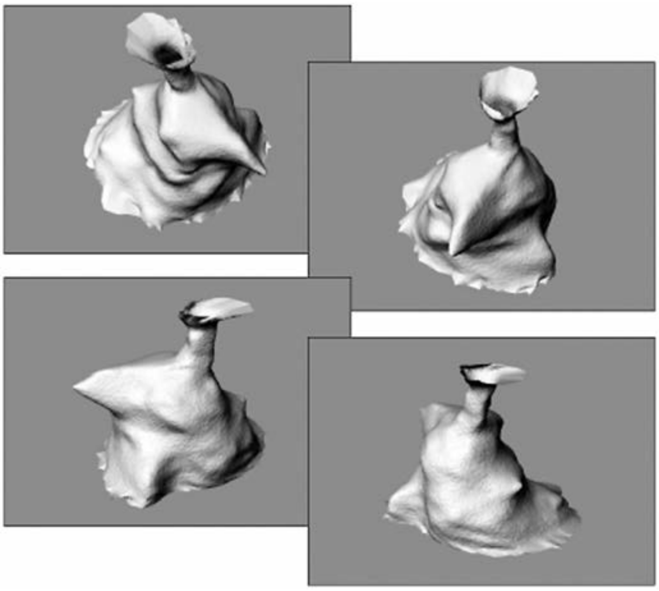


Figure 10. *Screen grabs from the resulting 3D Rhino model showing the highly irregular geometry of the cave feature encountered. For scale the height of each model represents 14m.*

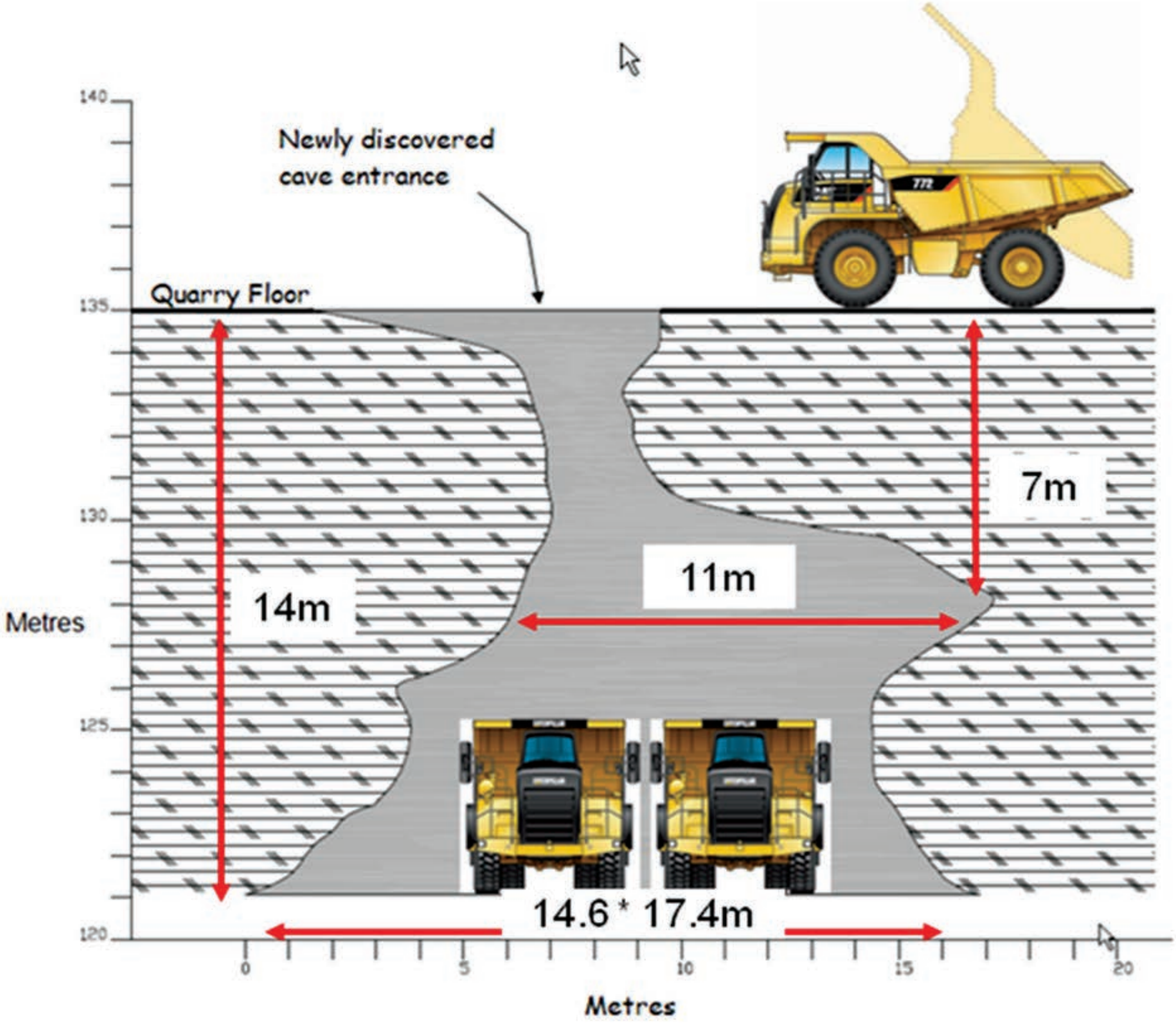


Figure 11. *Cross section of the cavity at its widest point. CAT 772 dump trucks have been added to provide perspective.*

Investigation stage 2: ROV survey

The sonar survey provided an excellent understanding of the caves geometry, but did not answer the concern of whether the probe had reached the bottom of the cavity or had grounded upon a ledge part way down, particularly after the initial dip had indicated a depth of 28m.

It was therefore decided that a Remote Operated Vehicle (ROV) survey would be undertaken to image the cave. The ROV used was a VideoRay Pro 4 (Figure 12) equipped with a high resolution colour camera optimized for underwater use. Due to its ultra low-light sensitivity, wide dynamic range and backlight compensation, it was able to provide detailed pictures in difficult lighting situations. The ROV was also fitted with a 3D Compass, a MEMS Rate GYRO, and a depth sensor, that was accurate to better than 2.5cm, allowing very stable auto depth and auto heading readings to be taken.

The large vertical pipe like formation (1.5m in diameter) to the top of the cave feature allowed access for the ROV to submerge and fly down into the main cavity. The ROV was able to determine that the sonar probe had come to rest upon the tip of a debris cone at the base of the cavern. Inspection of the materials showed it to be either covered in or formed from blasted rock which had filtered in to the hole during excavation and as a result of initial attempts by the quarry staff to backfill the cave. Images from the survey are shown in Figure 13.

Using the ROV's live video feed for navigation it was possible to explore the perimeter of the debris cone and the deepest parts of the cavity proving that the cave did not extend more than 4m beneath the point at which the sonar probe had come to rest. It also indicated that there was no flow of water within the cave system; there were no obvious outlets to the cave and, importantly, no side tunnels. The on-board gyro compass and depth gauge made it possible to tie in with the sonar survey and to provide a new interpretation of the cave as presented in Figure 14.

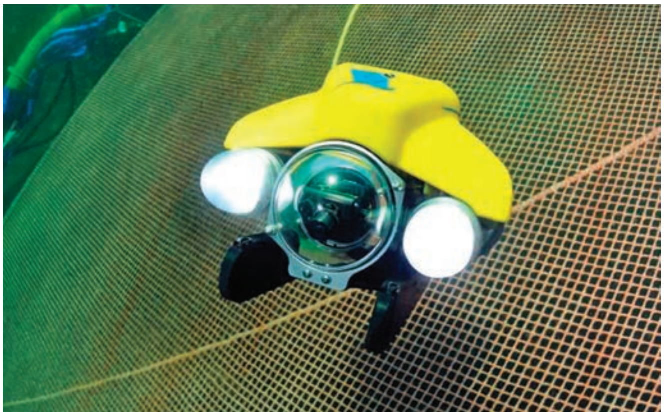


Figure 12. *Photograph of VideoRay Pro 4 ROV. Key statistics: dimensions; 375mm x 289mm x 22.3mm, weight ; 6.1kg, speed; 4.2 knots, dive depth; to 305m.*

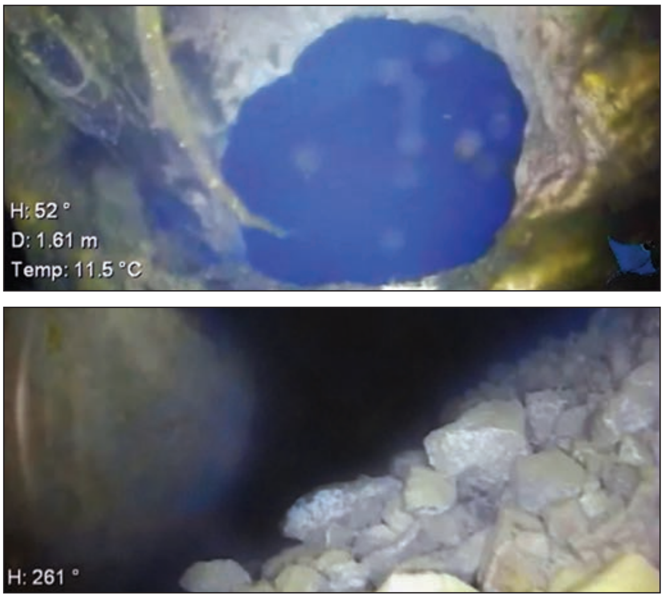


Figure 13. *Images from the ROV survey. The upper image shows the neck of the cavity. The lower image shows the freshly blasted rock forming the debris cone.*

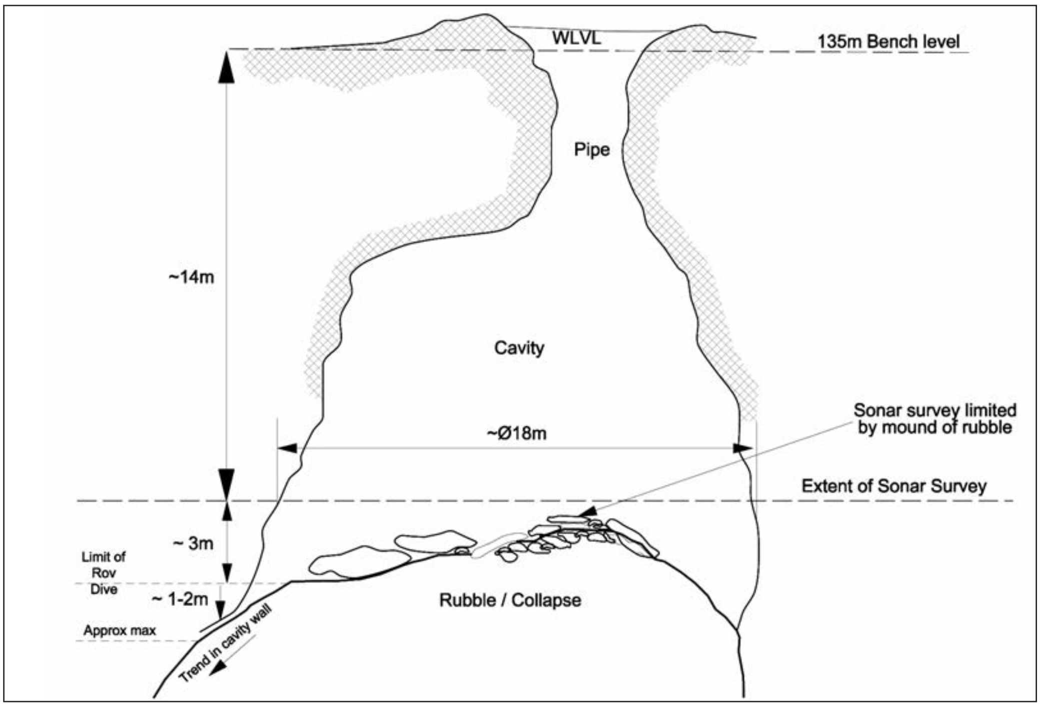


Figure 14. *Revised schematic cross section of the cavity following the ROV survey.*

Cave remediation

The cavern surveys proved valuable in that they provided an accurate and reliable understanding of the geohazards that the cavern represented. Immediately, on the day of the survey it was possible to state with certainty that the demarcation zone was adequate to keep plant and personnel safe on the site. The surveys also provided a tool by which Lafarge Tarmac was able to determine how best to remediate the problem. Backfilling the cave would have required plant and machinery to access the roof of the cave, and considering the irregular shape of the cave, it would not have been possible to confirm that the entire cave had successfully been backfilled. This led the company to consider stoving-in of the cavity through blasting, in conjunction with its drill and blasting contractors, BAM Ritchies.

Accurate cross sections were produced at intervals and orientations requested by the blasting contractor, allowing them to plan in detail their blast pattern, spacing and burdens. Unusually in this instance the burden was the distance from the blast holes to the open edge of the inside of the cave. An excerpt from the blast design is shown in Figure 15. As shown, the entire cave structure (to its full depth) was surrounded by blast holes, which when blasted would ensure that the roof was entirely broken and thus not leave any significant voids.

The resulting blast successfully stoved-in the cave. The resultant hole was then backfilled and levelled ready to accommodate quarry traffic once again.

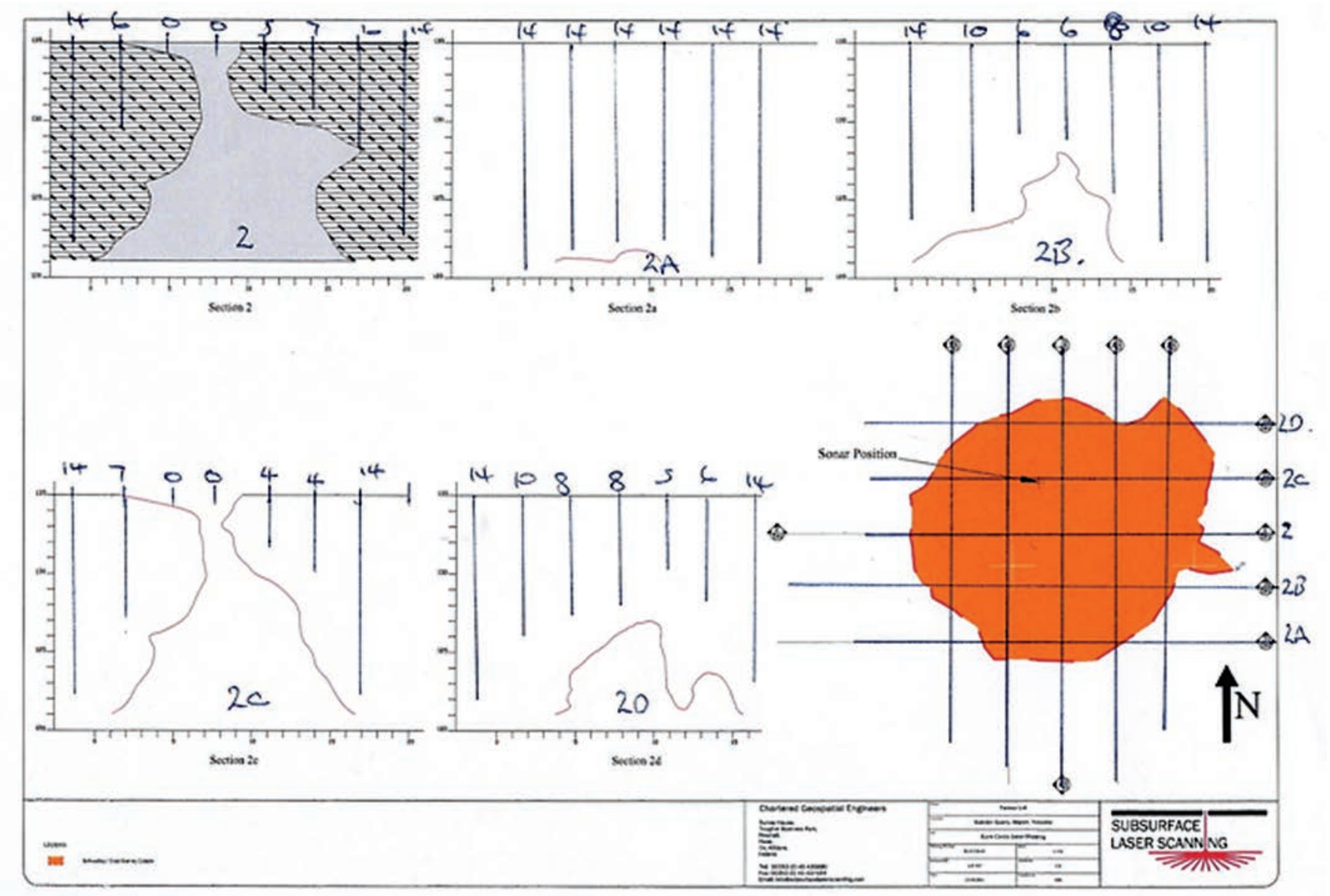


Figure 15. *Excerpt from BAM Ritchie's drill and blast design to stove-in the cave showing proposed blasthole positions completely surrounding the cave.*

CONCLUSIONS AND LESSONS LEARNT

Experience at Swinden Quarry has confirmed that managing cavities within a quarry remains a challenge, but that with changing technology, new techniques are becoming available to help operators manage and remediate the risk that they pose.

Choosing a practicable solution should be based upon a combination of factors, including cognisance of the potential for cavities arising from the local and regional geological setting, local experience and field mapping, characterisation of the nature of the cavities, constraints the local site conditions present, and ultimately what is at risk. Whilst it is always desirable to be proactive in risk management, cavities remain difficult to detect up front and it is the author's view that there remains a significant role for an observational, albeit reactionary approach. To be effective this necessitates all personnel working at the quarry to know what to look for and requires an effective reporting procedure to be in place.

Whatever system is chosen, it needs to be proportionate to the risk posed and should be constantly reviewed for effectiveness and benchmarked against technological developments.

The new techniques tested in the investigation of the 135m level cavity have proven that they represent an accurate and effective approach to investigating cavities once they have been identified. The level of detail and confidence provided are a great step forward from traditional non-penetrative and probe drilling techniques, allowing operators to quantify the risk that the cavity poses and to plan the remediation of the cavity with a greater level of confidence and certainty.

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